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Performance Evaluation of Propagation Models for LoRaWAN in an Urban Environment

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***Abstract*— Low-Power, Wide-Area Networks (LPWAN) are projected to support a significant number of devices within the Internet of Things (IoT). Long-Range Wide Area Network (LoRaWAN) is an open specification and emerging LPWAN connectivity solution for IoT platforms. However, LoRaWAN network performance in urban scenarios is a fundamental research topic with limited exploration and characteristic analysis. In this paper, ATDI ICS Telecom is used to investigate LoRaWAN radio network coverage at 868 MHz using the Okumura-Hata, COST-231 Hata, Extended Hata, and ITU-R 1225 propagation models. The predicted received signal strength simulation results are compared with real-world test measurements taken in the urban environment of Glasgow City to evaluate various propagation models' accuracy. The proposed work demonstrates ITU R 225 and Extended Hata over-estimated the real measured received signal strength power whereas, COST-231 Hata and Okumura-Hata under-estimated the same signal power. Our results and analysis give important insights into the performance, evaluation, and comparison of existing propagation models for IoT connectivity with LoRaWAN technology within an urban environment.**

Keywords—IoT; LoRaWAN; Propagation Model; Radio Coverage; ATDI ICS Telecom

I. INTRODUCTION

A. Background

It is estimated that connected Internet of Things devices will increase to 75.44 billion devices by 2025 [1], where this number is expected to increase further with time. Furthermore, LoRaWAN, as the leading low-power wide-area networks (LPWAN) technology for the IoT applications in terms of long-range transmissions, has been recently used in various IoT smart applications [2]. This raises LoRaWAN radio network coverage performance characterization as a significant research area for current and future IoT applications. Similarly, accurate network radio coverage evaluation is a vital necessity for any network deployment and LoRaWAN in our case. Subsequently, various propagation models have been used to characterize signal propagation in different environments and are the tool to achieve the best coverage prediction [3]. Thus, there is a strong need to analyze which of the existing propagation models efficiently model LoRaWAN radio network coverage in different specific geographical locations. The ability to incorporate the terrain information from ATDI software [4] while analyzing network coverage performance of a specific area, is very crucial in evaluating the accuracy of simulation results.

B. Motivation

LoRaWAN is a promising technology for the current and future connectivity of the IoT in all environments, however its network coverage performance is not fully explored. Hence, the main aim of this study is to explore the LoRaWAN network performance in an urban environment. Additionally, the ATDI ICS Telecom simulator has an advantage accessing most of the terrain details of a relevant geographical area of coverage, which is an important factor in simulation accuracy. Among others, ATDI ICS Telecom considers digital terrain model data, clutter data, map data, and building data of an area which adds to the accuracy of the predicted simulation results.

The main contributions of this paper are summarized as:

- Accurately simulating the radio coverage of LoRaWAN packet reception in an urban scenario (Glasgow) with ATDI ICS Telecom using several popular propagation models.
- Analyzing real-world measurements taken in Glasgow City for LoRaWAN propagation performance evaluation.
- Detailed analysis and comparison of four of the existing propagation models and the measurements to analyze the suitability of each of the propagation models in Glasgow City.

C. Paper Organization

This paper is organized as follows: Section II presents an overview of LoRa, LoRaWAN, and the investigated propagation models. Section III summarizes the related work. The measurement campaign for data collection is described in Section IV. Section V presents simulations set up in ATDI ICS Telecom. Section VI focuses on the performance analysis of the results. Finally, the conclusions are drawn in Section VII with future research directions.

II. LORA AND PROPAGATION MODELS

A. LoRa and LoRaWAN

LoRa is based on spread spectrum modulation technique derived with Chirp Spread Spectrum (CSS) technology. It was developed by Cycleo of Grenoble, France, and acquired by Semtech in 2012, a founding member of the LoRa Alliance. LoRa is usable within the license-free spectrum from 863 MHz to 870 MHz in Europe and from 902 MHz to 928 MHz in the USA. LoRa reliable radio network coverage is characterized by various combinations of the following parameters: Transmission Power (TP), Bandwidth (BW), Carrier Frequency (CF), Spreading Factor (SF), and Coding Rate (CR) [5]. The connection of the wide-area network of LoRa is called LoRaWAN and it is a network protocol stack that offers the architecture of LoRa technology on the MAC layer. Furthermore, the LoRaWAN network is made up of LoRa motes or end devices that send information to a LoRaWAN gateway which in turn sends it to a network server [6]. Whereas, end devices connect directly to a few gateways in a star topology in a single-hop style as shown in Figure 1.

Authors in [7], [8] evaluate and confirm LoRaWAN network architecture to enable long-range transmissions at a low cost. Whereby, the LoRaWAN protocol uses lower power consumption levels than other LPWAN technologies based on LoRaWAN architecture to provide reliable communication for mobile devices [9]. Likewise, the level of power consumption of LoRaWAN sensors determines their battery lifetime and the lifetime of the whole network.

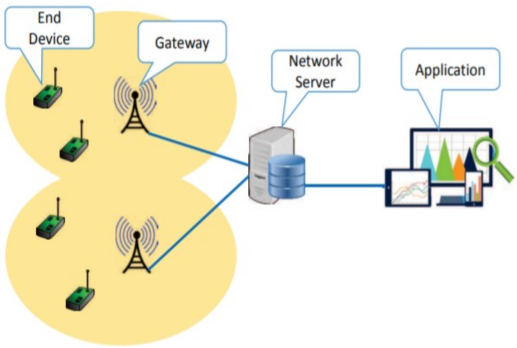

Figure 1: Frequent LoRa-based network architecture [10]

LoRaWAN scalability and range of coverage as reported by authors in [10], where according to their results, only three gateways are enough for a reliable radio network coverage of a dense urban city within a radius of 15 km. Also, they reported that each gateway can support up to 10^5 end devices. Additionally, in [11], the authors explore and confirm security robustness about LoRaWAN technology.

B. Propagation Models

In this section, we study some of the most frequently used propagation models that are used in LoRaWAN. The Okumura-Hata Model, COST-231 Hata Model, Extended-Hata and ITU R 1225 are considered in this study. Simulations of LoRaWAN network coverage in ATDI ICS Telecom are carried out and the received signal strength results from propagation models are compared with the measured data from Glasgow City.

1) Okumura-Hata Model: The Hata model is an empirical formulation of the graphical path loss data provided by Okumura and is valid from 150 MHz to 1500 MHz [12]. The median path loss in urban areas (PL_{urban}) measured in (dB) is given by:

$$PL_{urban} = 69.55 + 26.16 \log(f) - 13.8 \log(h_{te}) - a(h_{re}) + [44.9 - 6.55 \log(h_{te})]\log(d) \quad (1)$$

Where: f is the frequency from 150 MHz to 1500 MHz, h_{te} is the effective transmitter (base station) antenna height ranging from 30 m to 200 m, h_{re} is the effective receiver (mobile) antenna height ranging from 1 m to 10 m, d is the transmitter and receiver separation distance (in km), and ah_{re} is the correction factor for effective mobile antenna height which is a function of the size of the coverage area.

For a small to medium sized city, the mobile antenna correction factor (ah_{re}) is given by:

$$a(h_{re}) = (1.1\log(f) - 0.7)\, hre - (1.56\log(f) - 0.8) \quad (2)$$

And for a large city, it is given by:

$$a(h_{re}) = 8.29(\log 1.54 h_{re})^2 - 1.1 \quad \text{if } f \leq 300 \quad (3)$$

and if $f \geq 300$;

$$a(h_{re}) = 3.2(\log 11.75 h_{re})^2 - 4.97 \quad (4)$$

To obtain the path loss in a suburban area (PL_{Surban}) the standard Hata formula is modified as follows:

$$PL_{Surban} = PL_{urban} - 2[\log(f/28)]^2 - 5.4 \quad (5)$$

And for path loss in open rural areas (PL_{rural}), the formula is modified as:

$$PL_{rural} = PL_{urban} - 4.78[\log(f)]^2 - 18.33\log(f) - 40.98 \quad (6)$$

2) COST-231 Hata Model: This is an extension of the Okumura Hata model valid from 500 MHz to 2000 MHz.It is mostly used to predict link attenuation in mobile wireless systems. COST-231 Hata model can be used in urban, suburban and rural environments [12],[13]. Its basic equation for path loss in urban areas (PL_{urban}) is given by:

$$PL_{urban} = 46.3 + 33.9\log(f) - 13.82\log(h_b) - ah_m + [44.9 - 6.55\log(h_b)]\log(d) + c_m \quad (7)$$

Where: f is the frequency (MHz), d is the distance from the base station to the mobile antenna in (km), and h_b is the base station antenna height above ground level in m. The parameter c_m is defined as 0 dB for suburban or open environments and 3 dB for urban environments. The parameter ah_m is defined for urban environments as:

$$ah_m = 3.2[\log(11.75 h_r)]^2 - 4.97, f > 400 \quad (8)$$

and for path loss in suburban or rural environments:

$$ah_m = (1.1\log f - 0.7)\, h_r - (1.56\log f - 0.8) \quad (9)$$

where, h_r is the mobile antenna height in m above ground level.

3) Extended Hata: This is an extension of the Hata model (also known as Okumura-Hata). The Hata model was originally developed for Non-Line of Sight (NLOS) paths in an urban environment and later it was extended to predict outdoor propagation losses in the 30 MHz – 3000 MHz frequency band for urban, suburban and open area, hence developing another model named Extended Hata propagation model [13], [14] whose path loss (PL) is defined as:

$$PL = A_{fs} + A_{bm} - G_b - G_r \quad (10)$$

Where A_{fs} is the free space attenuation defined as:

$$A_{fs} = 92.4 + 20\ log10(d) + 20\ log10(f) \quad (11)$$

A_{bm} is the basic median path loss defined by the equation:

$$A_{bm} = 20.41 + 9.83\ log10(d) + 7.894 log10(f) + 9.56[log10(f)]^2 \quad (13)$$

G_b is the base station/gateway height gain factor defined as:

$$G_b = log10(hb/200)\ (13.958 + 5.8[log10(d)]^2) \quad (14)$$

G_r is the terminal end device height gain factor for medium urban areas defined as:

$$G_r = [42.57 + 13.7\ log10(f)]\ [log10(hr) - 0.585] \quad (15)$$

where, f is the frequency in GHz, d is the distance between gateway and end device in km, hb is the gateway antenna height in meters and hr is the end device antenna height in meters.

4) ITU-R 1225 MODEL: This is a radio propagation model defined by International Telecommunication Union radio communication (ITU). It is empirical and semi-deterministic path loss models that can be used in various environments including indoor, outdoor, pedestrian and vehicular in urban and suburban environments [15].
The ITU-R NLOS path loss (PL) is given by the following formula and defines the worst condition deviation of 10 dB for outdoor users.

$$PL = 40\ log(d) + 30\ log(f) + 49 \quad (16)$$

where d is the distance between the base station and the mobile unit in km. f is the frequency to 2000 MHz with the loss not to be less than the free-space loss in any circumstances.

III. RELATED WORK

Various research studies about LoRaWAN radio coverage using propagation models are present in literature. LoRaWAN path loss models were developed and compared to commonly used empirical propagation models such as Okumura-Hata, COST-231 Hata model and ITU-R model by El Chall et al in [16]. Using extensive real test measurements taken in both indoor and outdoor environments of urban and rural locations, the authors confirmed their proposed path loss models to be accurate and simple for LoRaWAN technology deployments in Lebanon and other similar locations, with coverage of 8 km in urban and 45 km in rural environments.
The authors in [17] compared the received signal strength real measured values with the radio frequency planning tool calculated values for Okumura-Hata Model, Irregular Terrain Model (ITM) and Irregular Terrain with Obstructions Model (ITWOM). Their results proved ITWOM's calculated values to be the closest to the real LoRaWAN measurements. Furthermore, R. Sanchez-Iborra, J et al in [18] compared LoRa topographic measured data and Okumura-Hata model results in various environments and showed that the received signal strength was above -130 dBm for the lowest LoRaWAN data rate, with 12 as the spreading factor. Moreover, LoRaWAN covered 7 km in urban and sub-urban and 19 km in rural environments. More to that, a difference between LoRaWAN observed and specified received signal strength values in an urban scenario for each LoRa Spreading Factor values was found by Aloys et al [19]. While, in [20], a constant difference of 27 dB received signal power between Okumura-Hata and the LoRaWAN measurements was observed. An enhanced modified multi-wall propagation model and a neural network propagation model were presented by the authors in [21] and [22] respectively. Finally, a comparative performance analysis of Okumura-Hata, COST-231 Hata and COST-231 Walfish-Ikegami (COST-WI) propagation models was performed using the NS3 simulator and the measurements in an urban environment by Harinda et al [23]. According to their results, the Okumura-Hata model showed higher accurate predictions whereas COST-WI showed lower accuracy. In all the above studies, the simulation tools used did not consider the nature of the terrain of the relevant geographic area. Moreover, no empirical semi-deterministic propagation models were investigated.

IV. FIELD TEST MEASUREMENTS

Field test measurements were carried out in Glasgow City and their results enabled validation of our simulation results. A LoRaWAN end device MultiTech mDot module controlled by a Raspberry Pi was used to send data to three LoRa SX1301-enabled Kerlink gateways. One gateway was placed at 30 m on top of George More building in Glasgow Caledonian University, another gateway 27 m on top of James Weir building at the University of Strathclyde, which is 1 km from the first one, and the last one on top of Skypark which is 3 km from the first one. The end-device module device was used to collect and transmits data to the gateways at walking speed over various locations, moving away from the gateways. Figure 2. shows a map of the analysed area with a LoRaWAN gateway and a path used by end device in collecting measurements.
Details of the procedures and methodology used in addition to all details of the measurement set up are reported in [24].

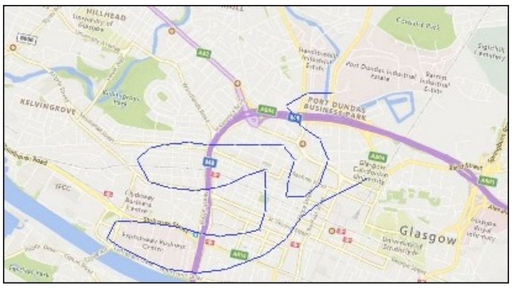

Figure 2: Map showing analyzed area with a LoRaWAN gateway, LoRa end device positions and the path used for collecting measurements (ATDI ICS Telecom Capture).

V. SIMULATIONS

The analysis of LoRaWAN radio coverage was performed using the ATDI ICS Telecom radio planning and spectrum management tool [4]. The important factor while simulating radio environment coverage is the quality of the map used and ATDI ICS Telecom software uses five cartographic layers that are important to consider while computing all the propagation parameters. Among others we have: Digital elevation models, clutter layer, map images, vector layer, and color palette. Table 1. contains some of the parameter settings used to configure the propagation loss models and the end device transmitter. Only the LoRaWAN gateway at Glasgow Caledonian University is considered during our initial simulation investigations.

VI. PERFORMANCE ANALYSIS

In this section, we analyze the LoRaWAN coverage, where four of the existing propagation models are used in ATDI ICS Telecom: Three empirical models: Okumura-Hata, COST-231 Hata and Hata Extended and One empirical semi-deterministic model: ITU R 1225 is compared to the real test measurements taken in Glasgow city. A coverage prediction of LoRaWAN modeling using parameters in Table 1 is presented in Figure 3.

TABLE 1: SIMULATION PARAMETERS

Parameters	Values
Frequency of operation	868 MHz
Bandwidth	125 KHz
Spreading factor (SF)	12
Gateway antenna height	50 m
Maximum distance between tx and rx	2275 m
End-device transmit power	14 dBm
End-device antenna height	1.5 m

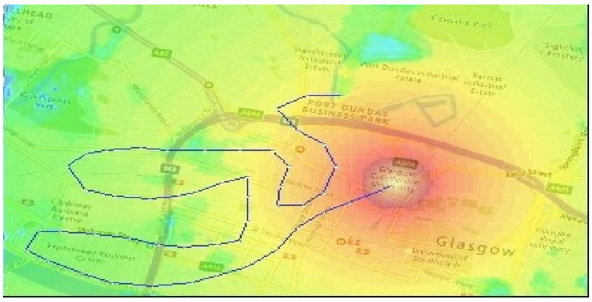

Figure 3: Coverage prediction of LoRaWAN from ATDI ICS Telecom

The analysis only considers NLOS conditions as a function of distance (m) and received signal strength (dBm) for one LoRaWAN gateway and one LoRa end device at different positions in Glasgow city. Packet loss in some locations can be taken to be caused by high density and several tall buildings present in Glasgow city. A comparative analysis between the results of the Propagation models and LoRaWAN real test measurement results is presented in Figure 4.

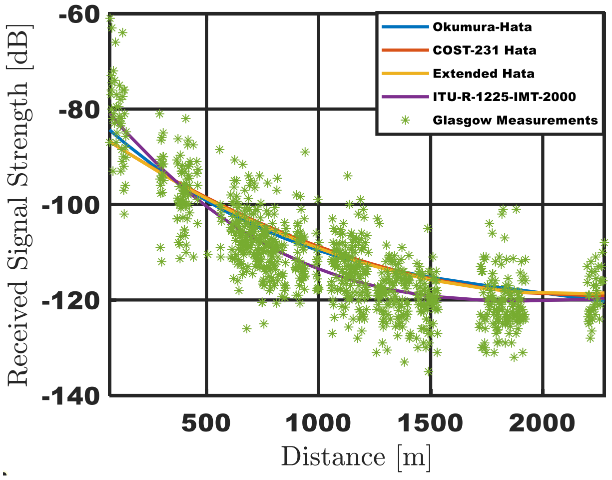

Figure 4: Comparative analysis between simulation results of the models and LoRaWAN real test measurement results

Our results show that ITU-R 1225 has the received signal strength values closest to the real measurements. Thus, the most accurate. While, Extended Hata model has received signal strength values far off from the measurements. Hence, the least accurate of the four investigated propagation models.

Three key performance metrics used in our evaluations are: Average Error (AE), the mean value of the difference between the real test measured received signal strength results x and the predicted received signal strength simulation results xi. The Mean Absolute Error (MAE) which is the average of all absolute errors between the measurements and the simulation results from the propagation model of interest. Standard Deviation (S) is also used to quantify the amount of dispersion of the predicted simulation results of each propagation model from the real test measurements. Table 2 shows the performance of each of the analyzed propagation model by comparing its simulation results to the real measured received signal strength data for n sample measurements, taken along the path on the map in Figure 2. The following formulae define the performance metrics:

$$AE\ (X) = 1/N \sum_{i=1}^{N} xi - x \tag{17}$$

$$\text{MAE}\ (\bar{X}) = 1/N \sum_{i=1}^{N} |xi - x| \tag{18}$$

$$S = \sqrt{\frac{\Sigma(X - \bar{X})^2}{N}} \tag{19}$$

TABLE II: ERROR PERFORMANCE METRICS

Error parameters	AE	MAE	STD
Okumura-Hata	-0.91	1.58	8.81
COST-231 Hata	-0.84	1.56	8.56
Extended Hata	0.58	1.82	9.19
ITU R 1225	0.29	1.13	5.49

According to our results, COST-231 Hata and the Okumura-Hata propagation models under-estimated the received signal power, for LoRaWAN network in Glasgow City. Whereas, ITU R 1225 and the Extended Hata models over-estimated the prediction of received signal power for the LoRaWAN network in Glasgow City. On the other hand, ITU R 1225 shows the highest accuracy of prediction with the least MAE of 1.13 dBm and a S of 5.49 dBm, which is the lowest diversion from the real measured received signal strength data. The least accurate propagation model is the Extended Hata model with a MAE of 1.82 dBm and a S of 9.19 dBm, which is the highest diversion of the four investigated models in relating to the measurements. Our results also indicate a strong resemblance in the performance of Okumura-Hata and COST-231 Hata models for LoRaWAN networks in Glasgow City.

VII. CONCLUSION AND FUTURE WORK

In this paper, LoRaWAN radio coverage at 868MHz is evaluated and analyzed via extensive simulations in ATDI ICS Telecom software, four propagation models: Okumura-Hata, COST 231 Hata, Extended Hata, and ITU R 1225 were used in in the urban environment of Glasgow. Real-world measured data collected using a LoRa transceiver at walking speed and the predicted simulation results of four different propagation models are compared. COST-231 Hata and the Okumura-Hata propagation models under-estimated the received signal power while ITU R 1225 and the Extended Hata models over-estimated the real-world measured signal power. Similarly, ITU R 1225 shows the highest accuracy with the least MAE of 1.13 dBm and a S of 5.49 dBm, which is the lowest diversion from the real measured received signal strength data. While, the least accurate propagation model is the Extended Hata model with a MAE of 1.82 dBm and a S of 9.19 dBm, which is the highest diversion in relating to the measurements of the four investigated models. Our results also indicate a substantial similarity in the performance of Okumura-Hata and COST-231 Hata models for LoRaWAN networks in Glasgow City. Our results give significant insights on the LoRaWAN performance and accuracy of four propagation models to be considered before any LoRaWAN IoT end device deployment in any urban environment. Our future work will include a study of LoRaWAN coverage with more LoRaWAN gateways, multiple end devices, and the effects of various parameter settings of physical layer LoRa Technology.

REFERENCES

[1] Statista Says a Five-Fold Increase in Ten years in Internet-Connected Devices by 2025 Will Significantly Increase the Internet's Promise of Making the World Connected,[online]Available:https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/ (Accessed April 11, 2020).

[2] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wirel. Commun.*, vol. 23, no. 5, pp. 60–67, 2016.

[3] Mollel, Michael & Kisangiri, Michael."Comparison of Empirical Propagation Path Loss Models for Mobile Communication". Computer Engineering and Intelligent Systems. Vol.5.no.9, pp.1-10,2014.

[4] ATDI ICS Telecom,available online at https://www.atdi.com,/ics-telecom (Accessed April 11, 2020)

[5] Semtech,''LoRaWANspecificationv1.1''. [Online]. Available: https://www.lora-alliance.org/technology(Accessed April 11, 2020).

[6] Semtech,''LoRaWANspecificationv1.1''. [Online]. Available: https://www.lora-alliance.org/technology(Accessed April 11, 2020).

[7] A. M. Yousuf, E. M. Rochester, and M. Ghaderi, "A low-cost LoRaWAN testbed for IoT: Implementation and measurements," *IEEE World Forum Internet Things, WF-IoT 2018 - Proc.*, vol. 2018-Janua, pp. 361–366, 2018.

[8] S. Sallouha, Hazem & Van den Bergh, Bertold & Wang, Qing & Pollin, "uLoRa: Ultra Low-Power, Low-Cost and Open Platform for the LoRa Networks," in *Proceedings of 4th ACM Workshop on Hot Topics in Wireless*, 2017, pp. 43–47.

[9] J. de C. Silva, Bounceur, Joel J. P. C. Rodrigues, Antonio M. Alberti, P. Solic, and Andre L. L. Aquino, "LoRaWAN - A Low Power WAN Protocol for Internet of Things: a Review and Opportunities," *2017 2nd Int. Multidiscip. Conf. Comput. Energy Sci.*, no. July, pp. 1–6, 2017.

[10] A. M. Yousuf, E. M. Rochester, B. Ousat, and M. Ghaderi, "Throughput, Coverage and Scalability of LoRa LPWAN for Internet of Things," *IEEE/ACM Int. Symp. Qual. Serv.*, 2018.

[11] I. Butun, N. Pereira, and M. Gidlund, "Analysis of LoRaWAN v1.1 security," no. June, pp. 1–6, 2018.

[12] Y. Singh, "Comparison of Okumura, Hata and COST-231 Models on the Basis of Path Loss and Signal Strength," vol. 59, no. 11, pp. 37–41, 2012.

[13] Mollel, Michael & Kisangiri, Michael. "Optmization of hata model based on measurement data using least square method: A case study in Dar es Salaam-Tanzania". International Journal of Computer Applications. Vol.102.no.4,2014.

[14] "Manual/Propagation Models/Extended Hata: Hata-and-HataSRD-implementation.pdf," 2013 [Online]. Available: http:// tractool.seamcat.org/wiki/Manual/PropagationModels/Extended-Hata (Accessed January 03, 2020)

[15] ITU-R M.1225, " Guide lines for Evaluation of Radio Transmission Technology for IMT-200", 1997.Available online at https://www.itu.int/rec/R-REC-M.1225/en (Accessed January 03, 2020)

[16] El Chall, Rida & Lahoud, Samer & El Helou, Melhem. (2019). LoRaWAN Network: Radio Propagation Models and Performance Evaluation in Various Environments in Lebanon. IEEE Internet of Things Journal. PP. 1-1. 10.1109/JIOT.2019.2906838.

[17] Souza Bezerra, Nibia & Åhlund, Christer & Saguna, Saguna & Jr, Vicente. (2019). Propagation Model Evaluation for LoRaWAN: Planning Tool Versus Real Case Scenario. IEEE 5th World Forum on Internet of Things.10.1109/WF-IoT.2019.8767299.

[18] R. Sanchez-Iborra, J. Sanchez-Gomez, J. Ballesta-Vi˜nas, M.-D. Cano, and A. F. Skarmeta, "Performance evaluation of lora considering scenario conditions," Sensors, vol. 18, no. 3, p. 772, 2018.

[19] Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of lora: Long range & low power networks for the internet of things," Sensors, vol. 16, no. 9, p. 1466, 2016.

[20] L. Feltrin, C. Buratti, E. Vinciarelli, R. De Bonis, and R. Verdone, "Lorawan: Evaluation of link-and system-level performance," IEEE Internet of Things Journal, 2018.

[21] S. Hosseinzadeh, H. Larijani, and K. Curtis, "An enhanced modified multi wall propagation model," in Global Internet of Things Summit (GIoTS), 2017. IEEE, 2017, pp. 1–4.

[22] S. Hosseinzadeh, M. Almoathen, H. Larijani, and K. Curtis, "A neural network propagation model for lorawan and critical analysis with real-world measurements," Big Data and Cognitive Computing, vol. 1, no. 1, p. 7, 2017

[23] E.Harinda, H. Larijani, and R. Gibson, "Comparative Performance Analysis of Empirical Propagation Models for LoRaWAN 868MHz in an Urban Scenario," in IEEE 5th World Forum on Internet of Things, 2019.

[24] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, and N. Strachan, "Evaluation of LoRa and LoRaWAN for wireless sensor networks," *Proc. IEEE Sensors*, vol. 0, pp. 5–7, 2017